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The long range goal of this project was to quantify the dynamical mechanisms by which mass momentum and energy are exchanged between the coastal and open ocean. Emphasis was placed on nonlinear mechanisms operating on sub-grid scales, dynamically consistent and quantitative methods for interpreting wuasi-Lagrangian data and non-linear/nonquasigeostrophic flow processes. It is hoped that this research contributes to improved parameterizations of sub-grid processes and to efficient utilization of quasi-Lagrangian data in predictive models. Two specific questions were addressed: Scientific Question 1: What is the role of secondary circulation on the exchange between the coastal and open ocean? Scientific Question 2: How can ocean eddies produce superinertial fluctuations in the hydrodynamic fields?

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ONR Final Report
Section A. Summary.

I.

A. D. Kirwan, Jr.
N00014-91-J-1560: *Nonlinear secondary oceanic flows: Their role in transport of mass, momentum and energy* (CORE)
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II. Progress Abstract

The long range goal of this project was to quantify the dynamical mechanisms by which mass, momentum and energy are exchanged between the coastal and open ocean. Emphasis was placed on nonlinear mechanisms operating on sub-grid scales, dynamically consistent and quantitative methods for interpreting quasi-Lagrangian data and nonlinear/nonquasigeostrophic flow processes. It is hoped that this research contributes to improved parameterizations of sub-grid processes and to efficient utilization of quasi-Lagrangian data in predictive models. Two scientific questions were addressed:

Scientific Question I: What is the role of secondary circulation on the exchange between the coastal and open ocean?

Working in collaboration with scientists at Naval Research Lab (NRL), National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC) and Rosenstiel School of Marine and Atmospheric Science (RSMAS), we analyzed historical advanced high resolution radar (AVHRR) data for the North Atlantic. The analysis differed in two fundamental ways from all previous studies. First, it used a new zebra palette false color scheme for resolving frontal structures. Unlike empirical orthogonal functions (EOF's) or other analysis routines often used in remote sensing studies, the zebra palette does not alter the pixel data. It merely provides a false color scheme that enhances the thermal boundaries. This palette is a variant of one developed by National Center for Supercomputing Applications (NCSA) and is commercially available. It is also easy to modify for use in different regions or seasons.

The other difference is a separatrix algorithm for tracking the evolution of frontal features associated with eddies and filaments. This method evolved from experience of the GSFC and RSMAS collaborators with the zebra palette. Its principal advantage vis-a-vis other methods

is that it requires less areal coverage and thus is less affected by cloud cover. In fact, preliminary results show a 100% increase in image utilization. The paper in preparation by Hooker et al. (1995), "Detecting "dipole ring" separatrices with zebra palettes," provides the technical details.

Application of these tools to the historical AVHRR data fundamentally altered our view of mesoscale and submesoscale processes at the coastal open ocean interface. These tools have shown that the warm core rings in the North Atlantic are not isolated monopole vortices as commonly thought. Instead, the zebra palette rendering of the images shows that the warm core anticyclonic rings are always accompanied by one or more daughter cyclones. They comprise a long-lived system of vortices that translate and rotate together.

The cyclones range in scale from deep structures as reported in the Warm Core Rings Program to shallow edge vortices associated with either the Gulf Stream or the shelf/slope front. Individual cyclones have been tracked for more than six weeks using these tools.

This finding has major ramifications for the coastal ocean interface. The rotation of the cyclone around the anticyclone and the consequent induced flow is the primary cause of the filaments and squirts so commonly seen in this zone. Moreover, we have analyzed in some detail, using a feature model of this phenomena, the cross-shelf transport induced by this vortex system. This calculation shows that three rings a year can account for all the cross-shelf transport required to balance the salinity and fresh water budgets for the Mid-Atlantic Bight shelf.

The new view of eddies as a system of translating and rotating vortices is not confined to the coastal open ocean region of the North Atlantic. Zebra palette and separatrix analysis of cold core cyclonic rings in the mid-Atlantic indicate daughter anticyclones. Similar analysis of AVHRR data from the South Atlantic shows even more vigorous vortex systems.

These findings impact both theoretical and observational studies. The dynamical balances required to maintain systems of vortices is strongly nonlinear and vastly different from the simple quasigeostrophic dynamics used to model isolated vortices. From the observational side it is now clear that hydrographic surveys need to extend well beyond the primary vortex. The findings also underscore the emerging importance of the quantitative use of remote sensing data.

<u>Scientific Question II</u>: How can ocean eddies produce superinertial fluctuations in the hydrodynamic fields?

We have addressed this issue with a nonlinear lens model. The key result is that the deformation in both the lens and the environment can excite both sub-and superinertial fluctuations of the hydrodynamic fields through the nonlinear terms in the hydrodynamic equations. The pathways for the interactions are described in "Nonlinear ocean dynamics" (Kirwan, Lipphardt and Gregory, *The Oceans: Physical-Chemical Dynamics and Human Impact*, 1994). Implications for both mesoscale and small scale oceanographers are discussed in "Coherent flows with near zero potential vorticity" (Kirwan and Lipphardt, *J. Mar. Sys.*, 1993).

This study indicates that super- and subinertial scale phenomena are more closely linked than heretofore believed. We have started applying some of the ideas developed in this effort to the dynamics of filaments and to our ARI, N00014-93-10567.

Section B. List of publications/presentations/reports: FY 92-94.

P- Toner, M., and A. D. Kirwan, Jr., 1994: Periodic and homoclinic orbits in a toy climate model. *Nonl. Proc. Geophys.*, **1**, 31-40.

P-Mullen, C. P., and A. D. Kirwan, Jr., 1994: Surface flow structure of the Gulf Stream from composite imagery and satellite-tracked drifters. *Nonl. Proc. Geophys.*, **1**, 64-71.

P-Kirwan, A. D., Jr., B. L. Lipphardt, Jr., and K. L. Gregory, 1994: Nonlinear ocean dynamics. *The Oceans: Physical-Chemical Dynamics and Human Impact.* The Pennsylvania Academy of Science. S. K. Majumdar, E. W. Miller, G. S. Forbes, R. F. Schmalz, and A. A. Panah, Eds.

P-Eremeev, V. N., A. D. Kirwan, Jr., and T. M. Margolina, 1994: Amount of 137Cs and 134Cs radionuclides in the Black Sea produced by the Chernobyl disaster. *J. Environ. Radiol.*, in press.

P-Eremeev, V. N., L. M. Ivanov, A. D. Kirwan, Jr., and T. M. Margolina, 1994: Analysis of the Cesium pollution in the Black Sea by regularization methods. *Mar. Poll. Bull.*, in press.

P-Ivanov, L. M., A. D. Kirwan, Jr., and O. V. Melnichenko, 1994: Prediction of the stochastic behaviour of nonlinear systems by deterministic models as a classical time passage probabilistic problem. *Nonl. Proc. Geophys.*, in press.

P-Tsonis, A. A., G. N. Triantafyllou, J. B. Elsner, J. J. Holdzkom II, and A. D. Kirwan, Jr., 1994: An investigation of the ability of nonlinear methods to infer dynamics from observables. *Bull. Am. Meteor. Soc.*, **75**, 1623-1633.

P-Lipphardt, B. L., Jr., R. P. Mied, A. D. Kirwan, Jr., and G. J. Lindemann, 1994: Evolution of a rotating modon in a primitive equation model. Elsevier volume of proceedings of Amsterdam vortex conference. *Modelling of Oceanic Vortices.* Verhandelingen Koninklilјke Academie voor Wetenschappen (KNAW) North Holland, Elsevier. C. J. P. van Heijst, Ed.

P-Kirwan, A. D., Jr., and B. L. Lipphardt, Jr., 1993: Coherent flows with near zero potential vorticity. *J. Mar. Sys.*, **4**, 95-115.

P-Kirwan, A. D., Jr., and J. Liu, 1993: Streaks in the vicinity of an oscillating front. *J. Geophys. Res.*, **98**, 2533-2542.

P-Mied, R. P., A. D. Kirwan, Jr., and G. J. Lindemann, 1992: Rotating modons over isolated topographic features. *J. Phys. Oceanogr.*, **22**, 1569-1582.

P-Kirwan, A. D., Jr., B. L. Lipphardt, Jr., and J. Liu, 1992: Negative potential vorticity lenses. *Int. J. Eng. Sci.*, **30**, 1361-1378.

PS-Mied, R. P., A. D. Kirwan, Jr., and B. L. Lipphardt, Jr., 1994: Rotating modons in a stratified ocean over isolated topography. *Dyn. Atmos. Oceans.*

PS-Hooker, S. B., J. W. Brown, R. P. Mied, G. J. Lindemann, and A. D. Kirwan, Jr., 1994: Modeling warm core rings as rotating modons. *J. Geophys. Res.*

PS-Ivanov, L . M., A. D. Kirwan, Jr., and T. M. Margolina, 1994: On the spectral reconstruction of scalar fields in oceanography. *J. Geophys. Res.*

PS-Holdzkom, J. J. II, S. B. Hooker, and A. D. Kirwan, Jr., 1994: A comparison of a hydrodynamic lens model to observations of a warm core ring. *J. Geophys. Res.*

PI-Hooker, S. B., J. W. Brown, and A. D. Kirwan, Jr., 1994: Detecting "dipole ring" separatrices with zebra palettes, for *IEEE Trans. Geosci. Remote Sensing.*

PI-Hooker, S. B., J. W. Brown, A. D. Kirwan, Jr., and R. P. Mied, 1994: Are Gulf Stream rings really monopoles?, for *Science*.

PI-Hooker, S. B., J. W. Brown, A. D. Kirwan, Jr., G. J. Lindemann, and R. P. Mied, 1994: A kinematic investigation of warm core ring dipoles, for *J. Geophys. Res.*

C-Kirwan, A. D., Jr., B. L. Lipphardt, Jr., and R. P. Mied, 1994: Multipole vortices in the Gulf of Mexico. AGU ASLO Ocean Sciences Meeting, 21-25 February, San Diego, Ca.

C-Kirwan, A. D., Jr., S. B. Hooker, J. W. Brown, R. P. Mied and G. J. Lindemann, 1994: Warm core rings: monopoles or dipoles? AGU ASLO Ocean Sciences Meeting, 21-25 February, San Diego, Ca.

C-Lipphardt, B. L., Jr., A. D. Kirwan, Jr., and R. P. Mied, 1994: Kinematics of dipoles from a baroclinic modon solution. AGU ASLO Ocean Sciences Meeting, 21-25 February, San Diego, Ca.

C-Holdzkom, J. J. II, A. D. Kirwan, Jr., C. E. Grosch, M. Zubair, and N. Kauser, 1994: Particle in cell simulations of coastal flows using massively parallel computers: preliminary results. AGU ASLO Ocean Sciences Meeting, 21-25 February, San Diego, Ca.

C-Mullen, C., and A. D. Kirwan, Jr., 1994: Surface flow structure of the Gulf Stream from composite imagery and satellite-tracked drifters. AGU ASLO Ocean Sciences Meeting, 21-25 February, San Diego, Ca.

C-Kirwan, A. D., Jr., B. L. Lipphardt, Jr., and R. P. Mied, 1994: Baroclinic rotating modons: exact solutions to the nonlinear potential vorticity equations. EGS XIX General Assembly, 25-29 April, Grenoble, France.

C-Toner, M., and A. D. Kirwan, Jr., 1994: Topology of a chaotic two-dimensional climate model. EGS XIX General Assembly, 25-29 April, Grenoble, France.

C-Kirwan, A. D., Jr., J. J. Holdzkom II, 1994: Dynamical systems aspects of a nonlinear hydrodynamic lens model. EGS XIX General Assembly, 25-29 April, Grenoble, France.

C-Kirwan, A. D., Jr., S. B. Hooker, and J. W. Brown, 1994: Monopole and dipole ring interactions with the Gulf Stream. EGS XIX General Assembly, 25-29 April, Grenoble, France.

C-Kirwan, A. D., Jr., C. E. Grosch, J. J. Holdzkom II, N. Kauser, and M. Zubair, 1994: Particle in cell simulations of MMPs: very large dynamical systems. EGS XIX General Assembly, 25-29 April, Grenoble, France.

C-Kirwan, A. D., Jr., 1994: The dynamics of steady-rotating baroclinic multipole vortex systems. International Conference on Nonlinear Dynamics and Pattern Formation in the Natural Environment (ICPF 94), July 4-7, Leehwenhorst Congress Centre, Noordwijkerhout, The Netherlands.

C-Kirwan, A. D., Jr., 1994: Particle in cell simulations of oceanic flow. International Conference on Nonlinear Dynamics and Pattern Formation in the Natural Environment (ICPF 94), July 4-7, Leehwenhorst Congress Centre, Noordwijkerhout, The Netherlands.

C-Kirwan, A. D., Jr., 1994: The inside story on ocean eddies. The University of South Florida, Department of Marine Science Alumni Research Symposium, 27 October, St Petersburg, Fl.

C-Kirwan, A. D., Jr., 1993: A historical perspective on prediction of atmospheric and oceanic flows. Chapman Conference on Fractals, Chaos, and Predictability in Oceanography and Meteorology, 20-22 September, Galway, Ireland.

C-Kirwan, A. D., Jr., 1993: Rotating modons in a stratified ocean: a dynamical systems view. Chapman Conference on Fractals, Chaos, and Predictability in Oceanography and Meteorology, 20-22 September, Galway, Ireland.

C-Lipphardt, B. L., Jr., R. P. Mied, A. D. Kirwan, Jr., and G. J. Lindemann, 1993: Evolution of a rotating barotropic modon in a primitive equation model. Netherlands Academy of Sciences, Modeling of Oceanic Vortices, August, Amsterdam, The Netherlands.

I-Kirwan, A. D., Jr., 1994: Ocean/shelf exchange. CCPO Visiting Scientist Lecture Series, 11 October, Norfolk, Va.

I-Kirwan, A. D., Jr., 1994: Coastal physical oceanography and chaos. SACLANT Undersea Research Centre, 19 January, La Spezia, Italy.

I-Kirwan, A. D., Jr., 1994: Ocean Eddies: the inside story. William & Mary, Department of Physics, 17 May 1994.Williamsburg, Va.

I-Kirwan, A. D., Jr., 1994: Quasigeostrophic multipole vortices, Department of Mathematics, University of Stuttgart, 3 May, Germany.

I-Kirwan, A. D., Jr., 1994: Modons: the inside story on ocean eddies. Mathematics Department, Brown University, 27 September, Providence, Ri.

I-Kirwan, A. D., Jr., E. E. Posmentier, J. J. Holdzkom II, M. Toner, 1993: Chaos and stochasticity in a toy climate model, EGS XVIII General Assembly, April, Wiesbaden, Germany.

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